Simulation of Net Primary Production (NPP) of *Picea abies* in southern Sweden

An analysis based on three forest growth models

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Summary

The potential Net Primary Production (NPP) under climate change was simulated by using two process based growth models, 3-PG and BIOMASS. Both models were run for two climate scenarios A2 and B2 during the period 2071-2100 and compared with simulations of reference climate (1961-1990). The simulated NPP of the 3-PG model was also compared with simulated output of NPP from the BIOMASS model, for *Picea abies* (Norway spruce) at Asa in southern Sweden. In addition, the simulation results from 3-PG were compared with the biomass production of the empirical growth model DT. Special objectives of this study were (i) to estimate 3-PG parameters for *Picea abies,* (ii) compare the simulated NPP under different climate scenarios A2 and B2, (iii) analyze the 3-PG model sensitivity towards change in temperature, rainfall and soil fertility and (iv) to compare the prediction of potential NPP between 3-PG and BIOMASS models. Climate data showed an increased precipitation during winter season and elevated temperature throughout the whole year. The development of dry mass (tones/ha) simulated through 3-PG had good correlation with values simulated through DT. The R^2 value for foliage dry mass, root dry mass, stem dry mass and total dry mass are 0.82, 0.94, 0.7 and 0.73 respectively. The relative increase in predicted NPP ranged between 26.8-48.4% and 55.5-101.6% for A2 and B2 scenarios, respectively. A sensitivity analysis was also conducted for the effect of rainfall, temperature and soil fertility on potential NPP simulated by the 3-PG model. The relative range of NPP under A2-scenario was 55.5-101.6% for the 3-PG model and 13.3-41.8 for the BIOMASS model. The corresponding value for the B2-scenario was 26.8-48.4 % for 3-PG and 10.7-29.7 for BIOMASS.

Key Words: Elevated temperature increased CO_2-concentrations, climate change, modeling, boreal.

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List of abbreviations used

1. 3-PG-Physiological Principles in Predicting Growth
2. APAR- Absorbed Photosynthetically Active Radiation
3. APARu- Absorbed Photosynthetically Active Radiation utilized
4. BFG- Biology of Forest Growth
5. CO_2- Carbon-di-Oxide
6. CRU- Climate Research Unit
7. dBH- Diameter at Breast Height
8. DM- Dry Mass
9. DT-Deep Thoughts, Forest based empirical growth model.
10. ECHAM-A2- Regional simulation made in A2-scenario with German ECHAM/OPYC3 General Circulation Model.
11. ECHAM-B2- Regional simulation made in A2-scenario with German ECHAM/OPYC3 General Circulation Model.
12. E_{max}- Daily maximum evaporation rate
13. ET- Evapo-Transpiration
14. E_T- Transpiration
15. f_W- Plant available water
16. GCM- General Circulation Model
17. GHG- Green House Gas
18. GPP- Gross Primary Production
19. Had-A2-Regional simulations made in A2-scenario with British Had AM3H General Circulation Model.
20. Had-B2- Regional simulations made in B2-scenario with British Had AM3H General Circulation Model
21. IPCC- Intergovernmental Panel on Climate Change
22. IUFRO- International Union of Forest Research Organisations
23. L*- One sided LAI
24. LAI- Leaf Area Index
25. MAI- Mean Annual Increment
26. Msl- Mean Sea Level
27. M_{soil}- Moisture content of soil
28. NPP- Net Primary Production
29. ^oC- Degree Celsius
30. PBM- Process Based Models
31. P_n- Net Photosynthetic rate
32. P_{nmax}- Maximum rate of photosynthesis
33. ppm- Parts per million
34. PPt- Precipitation
35. RCAO- Baltic Sear Regional Climate Model
36. R_d- Dark respiration

37. RH- Relative Humidity
38. SFA- Swedish Forest Agency
39. SI- Site Index, A relative measure of forest site quality based on the height of the dominant trees at a specific age (usually 25 or 50 years, depending on rotation length).
40. SLA- Specific Leaf Area
41. SMHI- Swedish Meteorological and Hydrological Institute
42. SRES- Special Report on Emission Scenarios
43. T_a- Mean air temperature
44. T_{avg}- Monthly average temperature
45. T_{max}- Monthly maximum temperature
46. T_{min}- Monthly minimum temperature
47. VPD- Vapour Pressure Deficit
48. W_F- Dry Mass of foliage
49. W_R- Dry Mass of roots
50. W_S- Dry Mass of stem
51. $_{smax}$- Nominal field capacity of soil

1. INTRODUCTION

In the recent past there has been a tremendous increase of atmospheric greenhouse gas (GHG) concentration and the increase is mainly due to emissions from fossil fuel combustion, land-use changes and industrial processes (Matthews and Caldeira 2008; Quadrelli and Peterson 2007). Increased GHG concentration during the 20th century has led to an increased mean surface temperature on the earth (IPCC 2007; Keeling and Whorf 2005) and the climate change is expected to continue during the 21st century (IPCC 2007). In northern Europe the mean temperature is predicted to increase 1–2 °C in summer and 2–3 °C in winter during the next 50 years (Carter *et al*. 2005). The temperature increase is expected to be more pronounced at higher latitudes (IPCC 2001) and the boreal coniferous forest regions in northern Europe is predicted to be greatly affected.

The increased temperature and CO_2 concentration is expected to increase the forest growth. Bergh *et al*., (2010) has indicated that climate change will influence a lot of physiological processes in evergreen coniferous forests of cold-temperate and boreal regions. The physiological processes influenced by climate change include phenology, seasonality of photosynthetic capacity, respiration, soil nutrient availability and effect of elevated CO_2 on photosynthesis (Havranek and Tranquillini, 1995; Ågren*et al*., 2007). These processes will influence the Net Primary Production (NPP), carbon sequestration and will result in increased forest yield (Bergh *et al*., 1998). Net primary production of Swedish boreal forests might increase by 20-40% over the next 100 years (Bergh *et al*. 2010). Several studies suggest that larger harvest levels will be available in the future because of climate change (Bergh *et al*. 2010; Briceño-Elizondo *et al*. 2006; Eggers *et al*. 2008; Kirilenko and Sedjo 2007; Pussinen *et al*. 2002). Poudel *et al.*(2010) projected that climate change based on the Intergovernmental Panel on Climate Change (IPCC) B2 scenario (IPCC 2001) will increase the forest biomass production by 34% in the next 100 years in north-central Sweden.

Besides the effects of climate change, forest production may vary with different production and management methods. Boreal forests are characterized by low productivity because of low nitrogen availability (Tamm 1991), which is indirectly an effect of soil temperatures that slow mineralization and decomposition rates of soil organic matter (Kirschbaum 2000; Vanhala *et al*. 2008). Bergh *et al.*(2005) showed that if nutrient availability is non-limiting, forest production can increase by 300% in northern Sweden and 80% in southern Sweden compared to current production. In addition, selection of species according to soil moisture, texture and structure might further increase forest productivity**.**

2. AIM AND OBJECTIVES

The aim of this report was to compare simulated NPP of Norway spruce (*Picea abies*) of two different process based growth models, BIOMASS and 3-PG, under present climate and based on future climate scenarios. The future climate scenarios are obtained with emission scenarios

A2 and B2. The models were validated by comparing the simulated value of reference period (1971-2000) to the observed data during the same period.

The main objectives of this study are to:

- Compare values of total DM (dry mass in tonnes/ha) simulated by empirical forest growth model Deep Thoughts (DT) with values simulated using 3-PG.
- Compare simulated NPP (Net Primary Production in kg C/m^2/year) of *Norway spruce* for two different climate scenarios, A2 and B2, during the period 2071-2100 in relation to reference scenario during the period 1961-1990.
- Sensitivity analysis of simulated NPP from the 3-PG model, as an effect of change in rainfall, change in temperature and change in fertility of soil.
- Compare the change in LAI (Leaf Area Index) in different level of soil fertility.
- Compare the predictions of potential NPP between 3-PG and BIOMASS models.

3. MATERIAL AND METHODS

3.1 Study Area

Figure 1. Location of Asa experimental forest

The study was conducted in Asa experimental forests. Asa is located in southern Sweden (Figure 1). The most widely distributed species in the region is Norway spruce. Other species found in the location are Scots Pine (*Pinus sylvestris*), Birch (*Betula spp*), Oak (*Quercus spp*) etc (Blennow *et al*., 2010). The co-ordinates of the location are 57°08' N, 14°45' E and altitude varies between 225-250 m.a.s.l. (Bergh *et al*., 2005). The site was planted with two year old Norway spruce seedlings after clear felling the previous stand. The mean annual temperature during growing season is around 11.5 °C.The mean annual precipitation is around 700 mm

(Bergh *et al*., 2005). About 25% of the annual precipitation is as snow (Örlander *et al*., 2000). The Site Index (SI) of the Norway spruce stand was ranged between 20-36 m with a median value of around 28m (Blennow *et al*., 2010). The soil in the area is mainly silty-sandy morraine. The soil moisture is classified as mesic (Blennow *et al*., 2010).

3.2 The 3-PG Model

The model 3-PG (Physiological Principles in Predicting Growth) was developed by Landsberg and Waring (1997). It is a simple process based stand level model which requires few parameter values and some stand data as inputs for simulation. The model can be applied to several sites. The model needs to be parameterized for individual species. 3-PG is a transition model between conventional mensuration based growth models and process based carbon balance models (Sands 2004; Landsberg *et al*., 2001).

3.2.1 Basic Concept of 3-PG model

The 3-PG model consist of five sub models: biomass production, allocation of biomass between foliage, roots and stems (including branches and bark); stem mortality; soil water balance and a module to convert stem biomass to variables of interest to forest managers (see figure 2).The sub models of 3-PG models are briefly explained here.

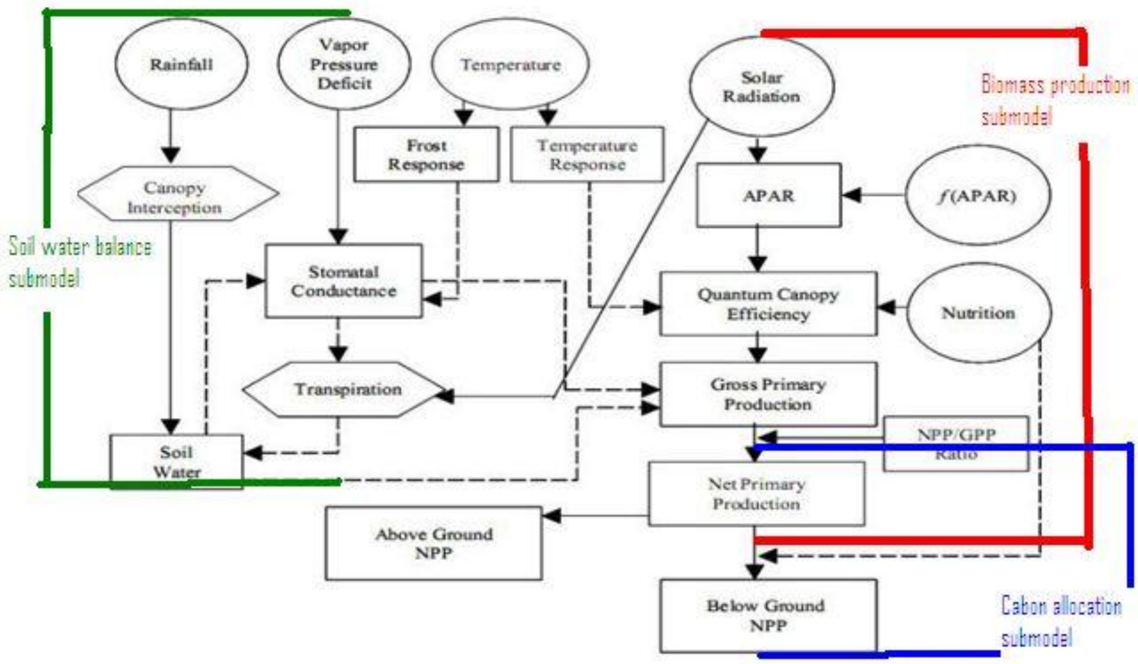

Figure 2. Conceptual diagram of 3-PG model

Source: Tickle *et al*., 2001

Biomass Production sub model:

The net solar radiation intercepted and utilized by the leaves was calculated using total incoming solar radiation and LAI of the tree species through Beer's Law (Sands, 2004). Absorbed Photosynthetically Active Radiation utilized (APARu) was a function of Absorbed Photosynthetically Active Radiation (APAR), which was reduced by constraint modifiers imposed by a) stomatal closure caused by high day time VPD (Landsberg and Waring, 1997), b) soil water balance which was the difference between total monthly rainfall and moisture stored in soil from previous month rainfall and transpiration calculated using Penman-Monteith equation (see eqn 1) (Coops *et al*., 1998), c) the negative effect of subfreezing temperature which was calculated using frost modifier calculated based on number of frost days per month. The value of frost modifier is between 0 (system shutdown) and 1 (no constraints) (Landsberg, 1986; McMurtie *et al*., 1994; Coops *et al*., 1998). Gross Primary Productivity (GPP) was calculated from APARu and canopy quantum efficiency. Net Primary Productivity (NPP) was considered to be a constant fraction of GPP (Coops *et al*., 1998).

$$\text{Soil water balance} = (1-i_R)\, Ppt_{total} - (M_{soil} + T) \tag{1}$$

Where

i_R = the fraction of rainfall intercepted subsequently evaporated from the canopy, Ppt_{total} = total monthly precipitation; M_{soil} = Moisture stored in soil from the previous rainfall; T = Transpiration from trees.

$$i_R = i_{Rx} \min(1, L/L_{ix}) \tag{2}$$

Where L= Leaf Area Index, L_{ix}= LAI where the trees has maximum interception of rainfall, When L was equal to L_{ix} the canopy interception is maximum. The excess of rainfall received at this point was lost as runoff or drainage (Sands, 2004).

Carbon allocation sub-model

The NPP produced through photosynthesis was allocated to other parts of the trees like roots, stem (including branches and bark) and foliage. Allocation of NPP to various parts depends on various environmental factors which act as constraints to photosynthesis (Coops *et al*., 1998). The environmental factors are determined by available soil water, VPD and site fertility (Sands, 2004). The NPP allocated to roots increases during adverse environment like less soil fertility or less available soil water. The allocation of NPP to foliage and stem depends on the dBH of the tree. As the dBH of the trees increases the allocation to foliage decreases and that to the stem increases (Sands, 2004).

Soil water balance sub-model

Soil water sub-model was based on the total monthly rainfall received which is balanced against evapo-Transpiration (ET) (Sands, 2004). The portion of the rainfall which is intercepted by the tree canopy is called the canopy rainfall interception. Canopy rainfall interception was directly proportional to LAI (Sands, 2004). Canopy conductance was a function of LAI and stomatal conductance. As LAI increases the canopy conductance increases. At maximum canopy conductance it is also affected by VPD, available soil water and stand age (Sands, 2004).

Mortality sub-model

Mortality sub-model was based on the concept of age dependent probability of tree death. It also considers the mortality caused by the long term stress factors such as water stress, pest and diseases etc (Sands, 2004). In this sub-model the changes in stocking is calculated based on the self thinning relationship which is based on the -3/2 power law (Drew and Flewelling, 1977). According to Sands (2004) an upper limit was estimated to mean single tree stem mass for the current stocking. When the current mean stem mass of the tree exceeds this limit, the population was reduced to a level corresponding to the limit.

3.2.2 Data inputs

The data inputs required for simulation in 3-PG are classified into three types

a) Climate data- monthly average of daily solar radiation (Q, $MJ/m^2/day$), mean air temperature ($T_{a,}{}^{o}C$) and day time atmospheric Vapour Pressure Deficit (VPD, mbar), total monthly rainfall(R, mm/month) and frost days ($d_{F,}$number of days per month).

b) Site specific data- Inputs required for site descriptions were site latitude; site fertility rating, maximum available soil water and soil texture (Sands 2004).

c) time series data- Inputs required for initial conditions of stand were foliage(W_F), stem including branches and bark (W_S) and root(W_R) dry biomass (ton_{DM}/ha), stocking density (N trees/ha), available soil water (mm). The basic unit of time used in 3-PG is day but most commonly basic unit of time is considered to be month.

3.2.3 Basic equations used in 3-PG model

Carbon balance equation

The carbon balance equations used in 3-PG were adapted from McMurtie and Wolf (1983). If x is the change in value of X over a time t days then

$W_F= n_FP_n-r_FW_Ft-m_F\ (W_F/N)\ n)$ (3)

$W_S=n_SP_n-m_S\ (W_S/N)\ n)$ (4)

$W_R=n_RP_n-r_RW_R-m_R(W_R/N)\ n)$ (5)

Where P_n= NPP in ton/ha/day, n_i= fraction of NPP allocated to the i^{th} pool, $r_{F=}$ litter fall rate per day, $m_{i\ =}$ fraction of biomass per tree lost in the i^{th} pool when a tree dies, r_R = root turnover rate per day, N= stem number (trees per ha) (Sands, 2004).

3.2.4 Data outputs

The outputs obtained from 3-PG are variables such as stand evapo-transpiration, NPP, specific leaf area and canopy leaf area index (Sands, 2004). Other stand level outputs which were familiar for forest managers like mean stem volume, mean annual Increment (MAI) and mean diameter at breast height (dBH) (Sands, 2004).

3.2.5 Assigning species specific values to 3-PG parameters

3-PG has to be assigned with species specific parameters. Usually the parameter values were assigned by direct measurement. The parameters of Norway spruce were obtained through literature review and also by trial and error method. In the trial and error method, the output data from 3-PG simulations are compared with DT simulation data.

3.3 The BIOMASS model

BIOMASS is a simple, dynamic, process-based model developed by McMurtrie (1985) under Biology of Forest Growth (BFG) experiment (McMurtrie and Landsberg, 1992). This model was developed to analyze the growth pattern of *Pinus radiata* in Northern New Zealand. It is a general tree growth model, considering tree canopy as a homogenous entity for all species (McMurtrie and Landsberg, 1992). The model assumes tree crowns either as truncated ellipsoids or cones (McMurtrie and Landsberg, 1992; McMurtrie *et al*., 1994).

3.3.1 Basic Concept of BIOMASS model

The BIOMASS model consists of two sub models such as: canopy photosynthesis model and water balance model (see figure 2) (McMurtrie *et al*., 1990).

Canopy photosynthesis sub model

Canopy photosynthesis sub model was based on the interception of incoming direct or diffused solar radiation by the tree canopy (McMurtrie *et al*., 1989). Canopy photosynthesis was estimated based on the one sided leaf area index (L*). In this sub model the tree canopy is assumed to be three different vertically arranged foliage layers (L^*_j, where $_j$= 1, 2, 3). Foliage in each layer was divided into three based on the interception of incoming solar radiation, such as sunlit foliage above light saturation (L^*_{1i}, where i= 1, 2, 3), sunlit foliage below light saturation (L^*_{2i}) and shaded foliage (L^*_{3i})*(McMurtrie *et al*., 1989). The division of L^*_{ji} into nine class change according to change in solar zenith angle during the period of the day.

Canopy photosynthesis is calculated separately considering the contributions from L^*_{1i}, L^*_{2i} and L^*_{3i}.

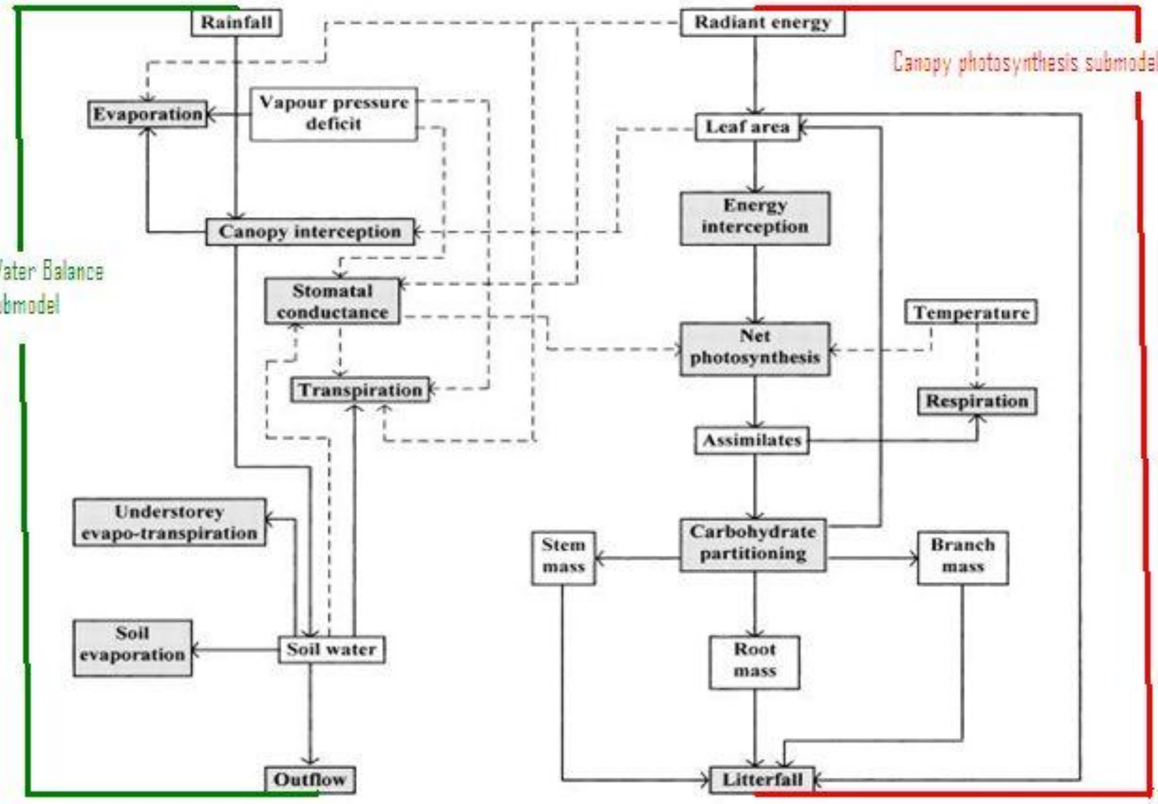

Figure 3. Conceptual diagram of BIOMASS model

Source: Bergh *et al*., 1998

Water-Balance sub model

Water balance model simulates the root zone soil water storage (McMurtrie *et al*., 1989). Soil water content in the root zone of plants depends on the daily incoming rainfall, evaporation of moisture from tree canopy, evaporation from under storey and evaporation from litter layer (McMurtrie *et al*, 1989). Transpiration from overstorey and understorey, drainage and runoff also influence soil water content in root zone (McMurtrie *et al*., 1989). The daily maximum evaporation rate (E_{max}) from a completely wet canopy was estimated using Penman equation (Jarvis, 1985) and from canopy interception rate (I). Soil drainage was explained by tipping bucket model in the BIOMASS model. The soil was assumed to be in two layers. The drainage from each layer occurs when the moisture content exceeds nominal field capacity ($_{smax}$) of each layer. Plant available moisture was defined as the amount of simulated moisture content of the root zone which exceeds the wilting point. The fractional plant available water (f_w) was the ratio of available water to the amount of available water at field capacity (McMurtrie *et al*., 1989). Transpiration (E_t) from the canopy was calculated using Penman-Monteith equation for a particular period of time t. Earlier models assume only soil water content as a driving variable for transpiration (Black, 1979; Dunin and MacKay, 1982). BIOMASS model calculates stomatal conductance as a function of $f_{w,}$ incident photon flux density on the foliage and Vapour Pressure Deficit (VPD) (McMurtrie *et al.*, 1989).

3.3.2 Basic equations used in BIOMASS Model

The net photosynthetic rate (P_n) was calculated from the incident photon flux density using Blackman equation (McMurtrie *et al.*, 1989).

$P_n=$ (1- $_1$- $_1$)}- R_d) (6)

Where P_n= net photosynthesis (kg C ha^{-1} day^{-1}), = Quantum yield, =solar zenith angle, $_1$= leaf reflectance, $_1$ = leaf transmittance, P_{nmax}= maximum rate of photosynthesis at ambient CO_2, R_d= Dark respiration rate.

McMurtrie (1989) has modified the Blackman equation in order to calculate the different contribution to daily canopy photosynthesis from foliage layers intercepting varying incident photon flux density. Daily net photosynthesis (kg C ha^{-1} day^{-1}) from sunlit foliage layer j with incident photon flux density above light saturation was calculated using the formula

(7)

The contribution to daily canopy photosynthesis was (kg C ha^{-1} day^{-1}) from sunlit foliage layer j with incident photon flux density below light saturation calculated by

(8)

The contribution of daily photosynthesis (kg C ha^{-1} day^{-1}) from foliage layer j due to interception of diffused radiation was given by

(9)

Where = day length, *Pnmaxj(t)* = light saturated photosynthetic rate in layer j for a period of day time t, = sunshine duration as a fraction of daylight period and R*d1j*was the daily respiration rate of sunlit foliage above light saturation, R*d2j*= daily respiration from sunlit foliage below light saturation, R*d3j*= daily respiration from foliage intercepting diffused radiation, Q2i = direct radiation intercepted in layer j during time t, Q3i was diffuse radiation intercepted in layer I during time t, = fraction of diffused radiation intercepted by the sunlit foliage above light saturation or below saturation.

3.3.3 Data Inputs

The data input required for BIOMASS were daily meteorological conditions, canopy characteristics, site specific data and foliage photosynthetic characteristics. Daily meteorological conditions required were maximum and minimum air temperature, total incoming daily shortwave radiation, humidity and total rainfall. Data input for canopy characteristics were initial foliage mass, LAI, Specific Leaf Area (SLA) and the distribution of leaf in space. Site specific data required were latitude, longitude, stocking, rooting depth, soil type, rooting depth, physical characteristics and physiological parameters for tree species. Input foliage photosynthetic characteristics required were maximum photosynthetic rate (A_{max}) and stomatal conductance (g_s).

3.3.4 Data Output

Data outputs obtained from BIOMASS model were NPP, LAI, Foliage, stem, root and total dry biomass, height, diameter and volume of stand.

Table 1. Simulated stand data using empirical growth model DT

Stand age	LAI	Foliage DM*	Stem DM	Root DM	Above Ground DM	Total DM
34	5,0	19,0	136,1	36,0	155,2	193,6
34 (after thinning)		13,1	94,6	26,8	107,7	134,5
39	5,5	16,1	132,3	36,6	148,4	185,0
44	6,0	19,1	172,0	47,0	191,1	238,1
49	6,5	21,4	210,3	56,2	231,7	287,9
49 (after thinning)	6,5	14,9	147,0	39,5	161,9	201,5
54	6,5	16,8	179,6	47,3	196,5	243,8
59	6,5	18,7	214,4	55,5	233,2	288,7
64	7,0	19,4	238,4	60,5	257,8	318,4

* DM= Dry Mass in tonnes per ha

3.4 Simulated data using empirical growth model

The total standing biomass was simulated using the empirical growth model Deep Thoughts (DT). Simulations were done in five year time-intervals. The initial age of simulation in DT was 12 and initial stocking was 2515 stems per ha. One pre-commercial thinning was done at the age of 12 to reduce the stem number to 2037 stems per ha. Two commercial thinning were done at the ages of 34 and 49 years. Both thinnings were done from below and around 40% of the total basal area was removed in each thinning. No application of fertilizers or irrigation has been considered in the simulations of DT in order to mimic the natural conditions for tree growth. Initial age for trees considered for this study is 34. Leaf Area Index (LAI), Dry Mass (DM) of foliage, stem, root and total DM are calculated separately in DT (see table 1). This output from DT was the initial input for the 3-PG stand initialization data. Foliage DM includes needle biomass; stem DM was the sum of biomass of bark, stem wood, live and dead branches. Root DM include stump and root biomass.

3.5 Climate Scenarios

A large number of emission scenarios were developed for all Green House Gas (GHG) emissions. In this study the multi gas emission scenarios developed by Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) have been used for simulations (Nakicenovic and Swart, 2000; IPCC, 2001). The climate scenarios used in this study are A2 and B2. A2-scenario considers a heterogeneous world with development concentrated in certain regions, slow economic growth and fast population growth (IUFRO, 2009).

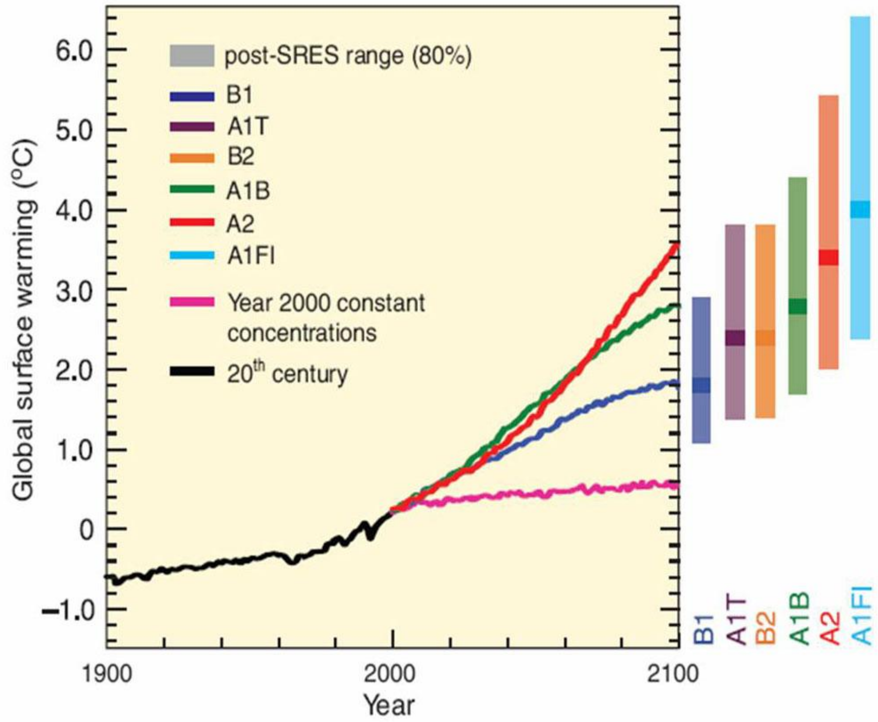

Figure 4. IPCC- SRES emission scenarios

Source: IUFRO, 2009

The climate scenarios used in this study is from Regional Climate Model simulations developed by Rossby Centre, Swedish Meteorological and Hydrological Institute (SMHI). All GHG emissions were considered in these scenarios but no anthropogenic depositions are considered. The simulations were done for 30 year periods, using Baltic Sea Regional Climate

Model (RCAO). A control run was made representing reference period (1961-1990) based on the CRU data set. Two scenario runs were made for A2- and B2-scenarios (2071-2100). The mean global warming according to Hadley Centre Model is $3.2^{o}C$ for the A2- and $2.3^{o}C$ for B2-scenarios (Nakicenovic and Swart, 2000; IPCC, 2001)(see figure, 1). The CO2 concentration for A2 scenario is 726 ppm and for B2 is 572 ppm during the year 2085 (Nakicenovic and Swart, 2000; IPCC, 2001). This value is considered as mean value for whole scenario run. The scenarios also indicate large increase of temperature during winter and smaller increase during summer (IUFRO, 2009; IPCC, 2001).

Table 2. Assumptions in A2- and B2- scenarios

Features	A2-Scenario	B2-scenario
Emission level of GHG	Higher emission level	Lower emission levels
Emission control measures	Business As Usual no control measures undertaken	Control measures undertaken
Development of world	Heterogeneous world with development concentrated in certain regions	Homogenous world
Economic growth	Slow	Intermediate
Technological development	Slow	Better technological development than A2
Population growth	Fast	Moderate

Source: IUFRO, 2009; Bergh et al., 2010

3.6 Simulations

The 3-PG model was used to simulate the potential NPP in *Norway spruce* for Asa. Three runs were made with 3-PG model, one reference run and two scenario runs (A2 and B2). Initial stand and site factors were obtained from Bergh *et al.*, (2003, 2009). The potential NPP was calculated for reference run for the period 1961-1990. This was compared with the estimated NPP for A2- and B2-scenarios for the period 2071-2100.During simulation of reference run, the total standing biomass output from 3-PG was compared with that simulated with the DT model. The simulations of 3-PG were repeated and the parameter values of the model were changed in order to get a better fit to the total standing biomass simulated with DT (see figure 4).

Once a good fit was obtained the parameter values of 3-PG model was fixed. These parameter values were used for further simulations using scenario climate. The timing of commercial thinning operations was according to the standard thinning schedule. Two thinning operations from below with intensity around 40% removal, were done at a stand age of 34 and 49 years (SFA, 1985). According to Blennow *et al.*, (2010) the regeneration felling was fixed when the mean annual increment (MAI) was less than 3%, which became 64 years in this study. Similar simulation was done with BIOMASS model for *Norway spruce* in Asa (Bergh *et al.*, 2003, 2009). The 30 year observation period is divided in to six 5-year period of growth. Five year average values of estimated NPP, climatic data and other growth factors are considered for comparison study between 3-PG and BIOMASS (see figure 5).

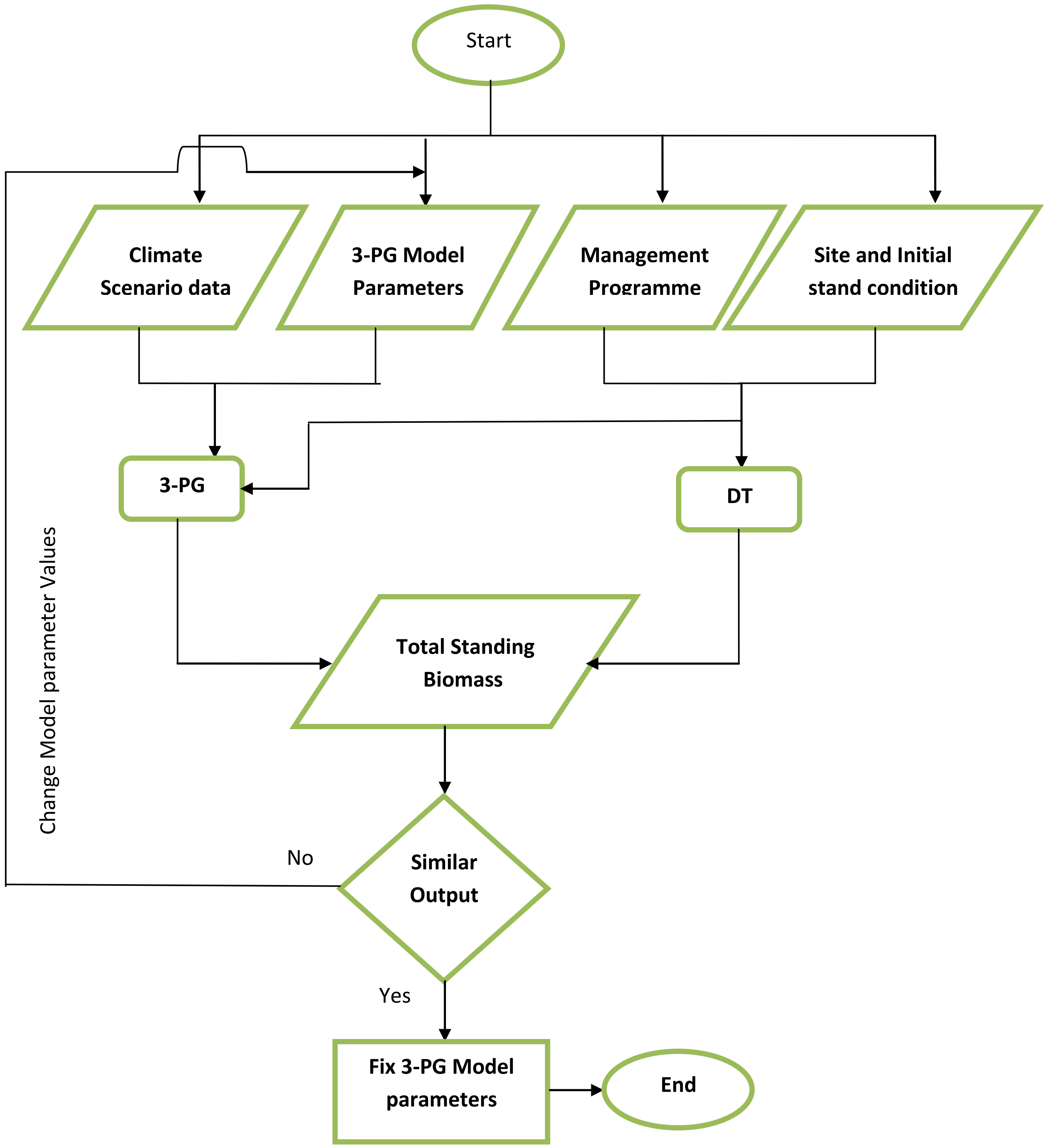

Figure 5. Flow chart of fixing parameters for 3-PGmodel, comparing 3-PG model output with DT model output.

3.7 Simulated NPP using BIOMASS model

According to Bergh *et al*., (2010), boreal-adapted version of BIOMASS was used to simulate the potential NPP for *Norway spruce* stands at Asa. The climate scenarios and initial stand and site factors used in simulation of NPP in 3-PG model were also used in simulation of NPP in BIOMASS model. The initial stand and site characteristics and some parameter values for the BIOMASS simulations, were obtained from Bergh *et al*. (2003) Bergh *et al*. (2009).

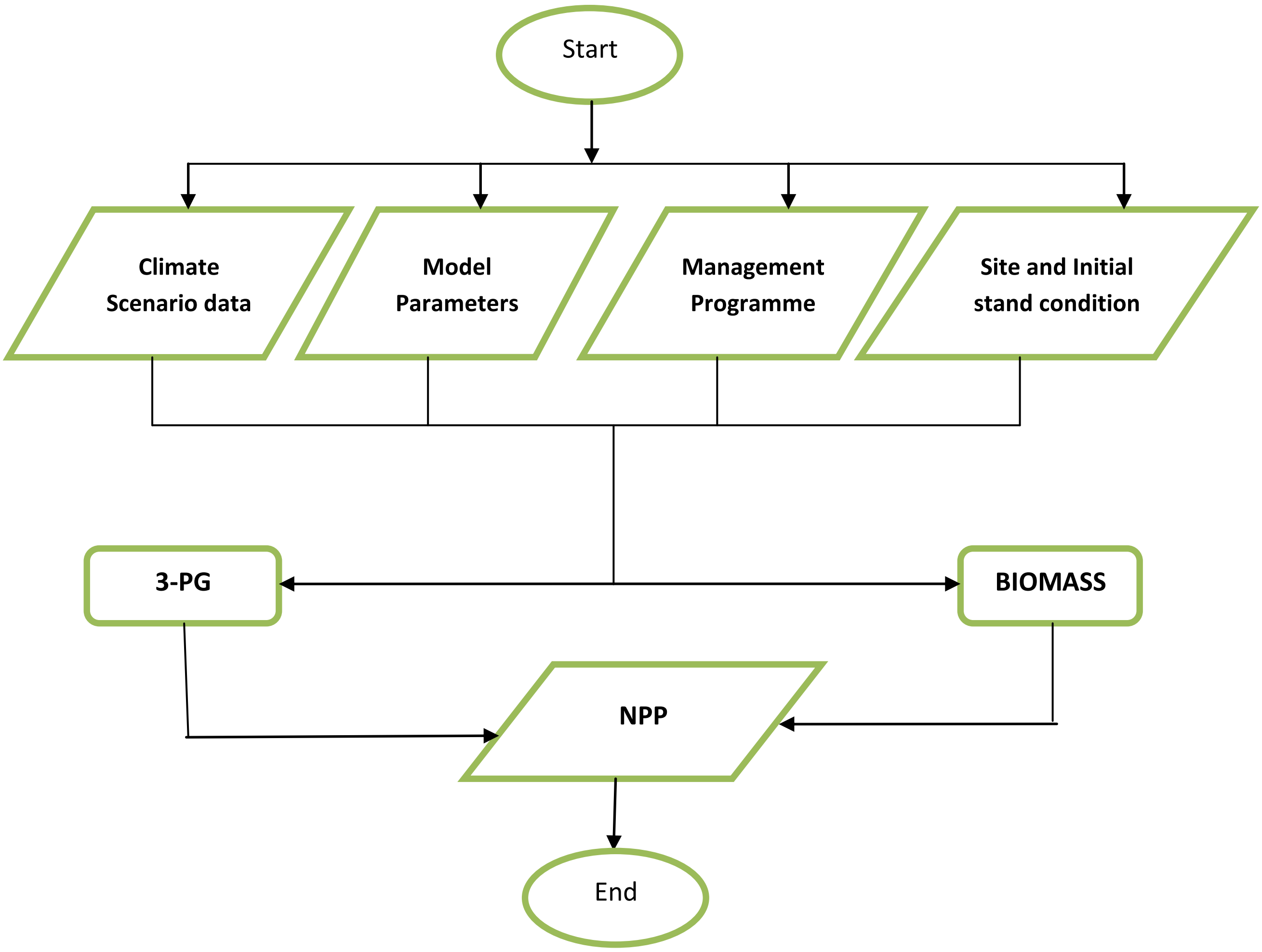

Figure 6. Flow chart of simulations and comparison of NPP made in 3-PG and BIOMASS models

3.8 Analysis of Climate data

The climatic variables such as monthly maximum temperature (T_{max}), monthly minimum temperature (T_{min}), total monthly rainfall, average monthly incoming solar radiation, number of rainy days per month and number of frost days per month were obtained from the Rossby Centre. The most important climatic variables with respect to tree growth were T_{max}, T_{min} and total monthly rainfall. These variables were analyzed in order to find a pattern of variation. Monthly temperature (T_{avg}) is the average value of T_{max} and T_{min}. $T_{avg} = (T_{max}+T_{min})/2$. Five year average value of T_{avg} and total monthly rainfall were taken correspondingly for the years 2071-75, 2076-80, 2081-85, 2086-90, 2091-95 and 2096-2100. In order to analyze the variation of climatic variables from the baseline scenario the five year average values of T_{avg} and total monthly rainfall in scenario run was subtracted with corresponding value in baseline scenario.

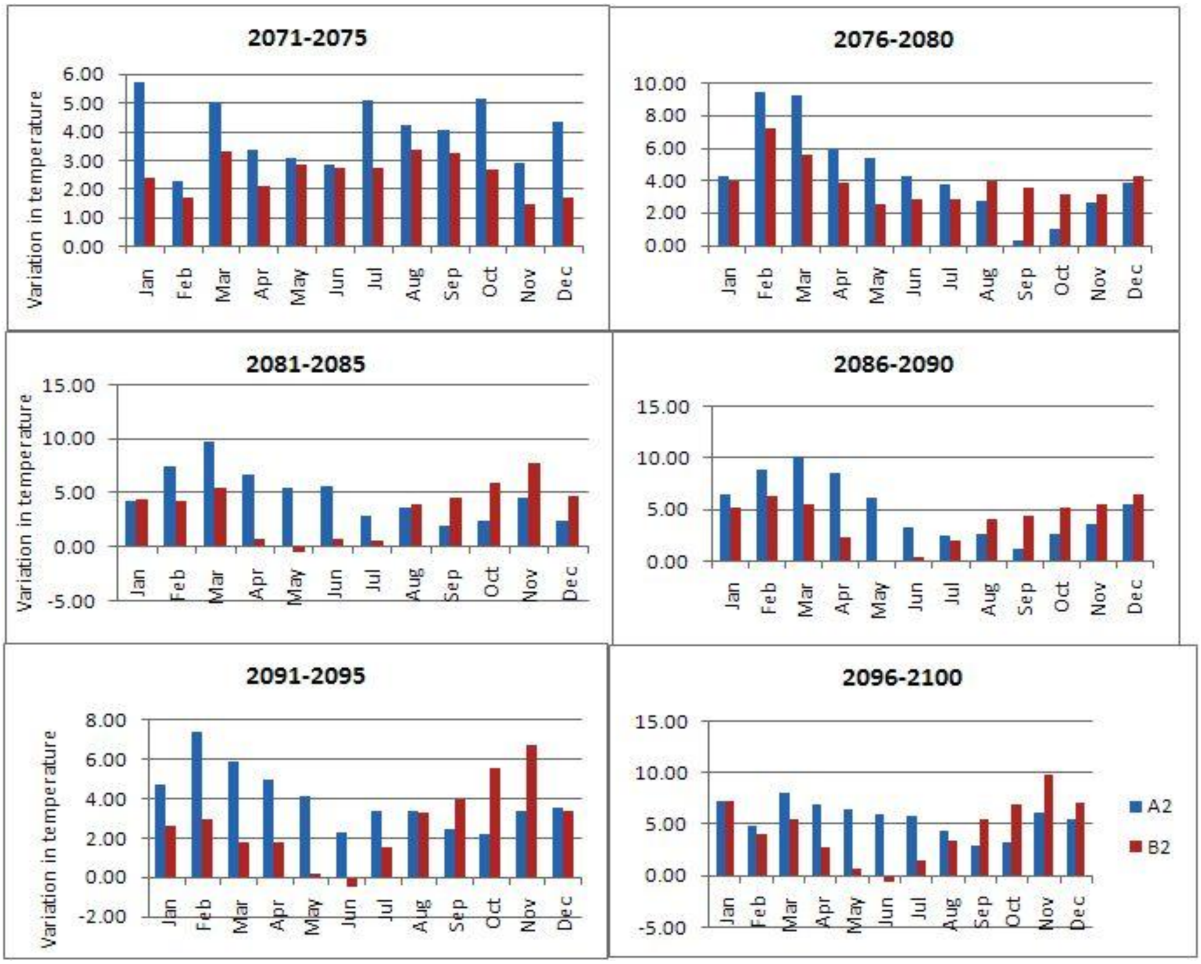

Figure 7. Variation in monthly average temperature (^{o}C) in A2- and B2-scenarios when compared with the reference temperature. Calculations are done in five year average values.

3.9 Comparing Climate data

The scenario climatic variables such as total monthly rainfall and monthly average temperature (T_{avg}) were analyzed in order to detect any pattern of variation from the reference climate. Five year average values of climatic variables were considered in this analysis.

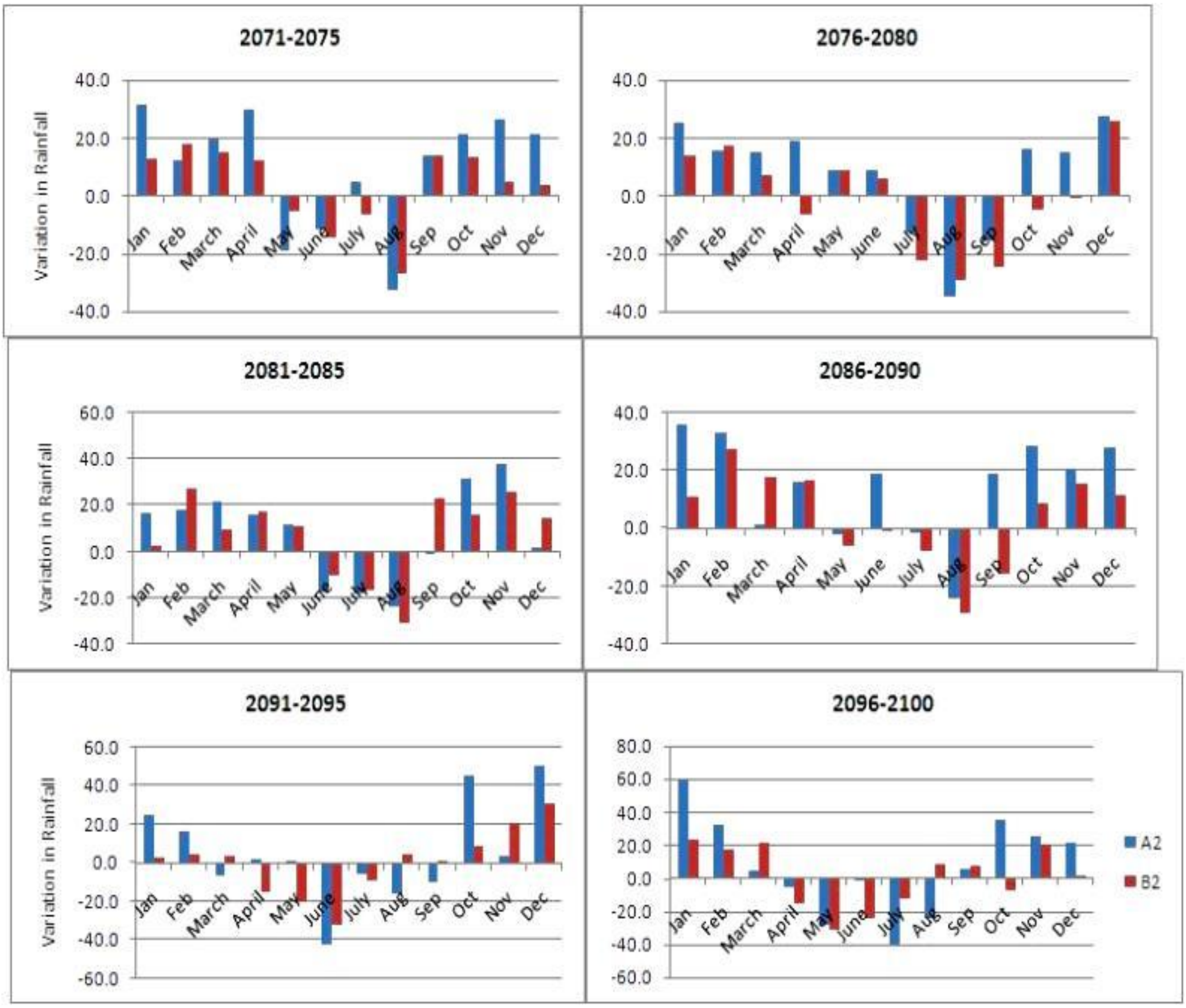

Figure 8. Variation in total monthly rainfall (mm) in A2- and B2-scenarios when compared with the reference rainfall. Calculations are done in five year average values.

3.9.1 Temperature in A2- and B2- scenarios

During the years 2071-2075 the temperature in A2-scenario shows higher value than B2 scenario for the whole year (fig. 6). However, during all other 5-year periods the A2-scenario showed higher average monthly temperature during January to July and lower average monthly temperature in August to December compared with the B2-scenario. This was because A2-scenario showed higher temperature during summer whereas the B2-scenario showed higher temperature during autumn and winter (fig. 6). The general observation in the scenarios was larger increase in winter temperature than summer temperature (Bergh *et al*., 2010). It is a general predicted trend that the difference between A2- and B2-scenarios will increase during this century.

3.9.2 Total monthly rainfall in A2- and B2-scenarios

There was an increase in rainfall during winter season in A2- and B2-scenarios, where the increase in rainfall is higher in A2-scenario (fig. 7). Both scenarios showed lower rainfall than the reference climate during the months July-September. A2-scenario also showed lower total monthly rainfall during July to September compared with B2. A general observation was that during late summer and beginning of autumn the precipitation is far less compared to C scenario. The increased precipitation was generally found during the winter season (fig. 7) (Bergh *et al*., 2010).

3.10 Parameter Estimation for *Norway spruce* for 3-PG model

Validation and fine-tuning parameter values was done to fit model output of baseline scenario to observed data. The parameter adjustment was done by assigning values to each parameter to get a better fit with the observed data. The 3-PG model was characterized by species specific parameters for individual species (Sands, 2004). Obtaining reliable parameter value was therefore important for using 3-PG in forest management. In this study parameter values were estimated in analogy with *Pinus radiata* values. Some parameter values were obtained from previous simulation work done by Bergh *et al*., (2003, 2009) on *Norway spruce* using BIOMASS model. Trial and error process were also used to get good fit of predicted values with observed values. Important parameters and their values for *Norway spruce a*re given in the Appendix 1.

3.11 Comparing simulated data

3.11.1 Comparing DT simulation with 3-PG simulation

The stand variable used for comparison of data simulated using DT model and that simulated using 3-PG model (reference scenario) are foliage Dry Mass (DM), stem DM and root DM, total standing DM. The DT simulation was compared to reference run of 3-PG for the 30-year time period (1961-1990). Simulated DM (in tonnes DM/ha) of foliage, stem, root and total DM of 3-PG were compared to corresponding DT-output to analyze the accuracy of 3-PG estimations. Parameter values were slightly changed to adjust the values of 3-PG output to get a better fit to the observed data.

3.11.2 Comparing NPP simulated in reference run and scenario runs using 3-PG model

Net Primary Production (NPP) of the whole tree is an output in 3-PG model. NPP output variable in 3-PG is calculated in tonnes DM/ha/month. Annual NPP is the sum of all monthly NPP during the year. For the comparison study with BIOMASS and earlier simulation studies, NPP is converted in to the standard unit of kg C/m^2/year. The five year average value of annual

NPP is calculated to simplify the comparison. The average NPP for the reference period is compared with the two scenarios.

3.11.3 Comparing simulated Leaf Area Index (LAI)

The LAI was an output in 3-PG model. The LAI was calculated for different fertility levels of soil like 0.5 (reference soil fertility), 0.6 (soil fertility level in A2- and B2-scenarios) and 0.7(Increased soil fertility). The change in LAI under increased level of soil fertility was analysed.

3.11.4 Comparing simulated NPP between 3-PG and BIOMASS models

The predictions of percentage change in potential NPP is compared between the two models, 3-PG and BIOMASS. The percentage change in potential NPP in the scenarios is calculated in relation to that in reference scenario. The range of values gives the lowest and highest value of change and mean represents the mean value of percentage change in whole growth period were used in this comparison (adapted from Bergh *et al*., 2010). The data for BIOMASS model is collected from Bergh *et al*., (2010). Two types of Global Circulation Model (GCM) data were used in simulating the A2- and B2- scenarios while simulating potential NPP in BIOMASS model (Blennow *et al*., 2010). Regional climate scenario based on Hadleys General Circulation Model (HadAM3H GCM) (Pope *et al*., 2000; Blennow *et al*., 2010) and the simulation done with regional climate scenario based on ECHAM/OPYC3 GCM (Roeckner *et al*., 1999; Blennow *et al*., 2010).

3.12 Sensitivity analysis of the 3-PG model

The sensitivity of a simulation model depends in first hand on the model but also the set of parameter values used for simulation, which influence on calculation of growth. The climate variables chosen for sensitivity analysis are maximum and minimum temperature, total monthly rainfall, soil fertility and LAI (Leaf Area Index). These climatic variables were key determinants of estimating potential NPP for scenarios. Initial stand conditions were not considered for sensitivity analysis, since 3-PG output for mature stands is independent of initial stand conditions (Sands and Landsberg, 2002). A comprehensive analysis of sensitivity of 3-PG output to species specific parameters was done by Esprey *et al*., (2004) with *Eucalyptus grandis*. The relative sensitivity was determined by running the model with reference value for each climate dataset separately (Esprey *et al*., 2004). Sensitivity of the model to a particular climatic or site factor was calculated assuming a condition where there was no change in that particular factor in the future. While all other climatic and site related factors vary according to prediction of scenarios. The resulting annual NPP (kg C/m^2/year) output of the model from the sensitivity analysis run was used for comparison. The effects of average monthly temperature, total monthly rainfall, and soil fertility on potential NPP were studied in different simulations.

3.12.1 Calculation of sensitivity of 3-PG model to rainfall

The annual NPP (Kg C/m^2/year) estimated from scenario rainfall is compared to that calculated with reference rainfall. The percentage change of annual NPP is calculated by the formula:

% change in NPP= $NPP_{(reference\ rainfall)} - NPP_{(scenario\ rainfall)}/NPP_{(scenario\ rainfall)}$ %

3.12.2 Calculation of sensitivity of 3-PG model to temperature

In order to analyze the temperature sensitivity of the 3-PG model, a sensitivity analysis run is performed with decreased monthly average T_{min} and T_{max}. The simulated NPP using reference temperature is compared with simulated NPP where monthly average T_{min} and T_{max} is decreased (see table 6). In order to compare the percentage change of NPP is calculated using the formula:

% change in NPP= $(NPP_{(reference\ temperature)} - NPP_{(scenario\ temperature)})/NPP_{(scenario\ temperature)}$

3.12.3 Calculation of sensitivity of 3-PG model to soil fertility

In the simulations done in this study, the fertility level of soil was almost the same for the reference period (0.5) and the scenarios (0.6).The percentage change in NPP as an effect of soil fertility is calculated using the formula:

% change in NPP= $(NPP_{(reference\ fertility)} - NPP_{(scenario\ fertility)})/NPP_{(scenario\ fertility)}$ %

4. RESULTS AND DISCUSSION

4.1 Comparison of simulated data using DT model with Reference scenario simulated using 3-PG model

The stand variable used for comparison of data simulated using DT model and that simulated using 3-PG model (reference scenario). The foliage Dry Mass (DM), stem DM and root DM, total standing DM data, simulated with DT, is shown in table 3. The average differences in foliage, stem, root and total DM between DT and 3-PG simulations were 2.4%; 1.8%; 12.7% and 3.6% respectively.

To assess the accuracy of prediction of 3-PG, scatter plots are generated for reference run with 3-PG and corresponding values simulated using DT. The variables compared are foliage DM, stem DM, root DM and total DM (figure 8-11). The foliage DM, stem DM and total DM were slightly underestimated by the 3-PG when compared with DT-simulations (Table 3, fig. 8). The loss of DM during thinning was also underestimated in 3-PG compared to the DT-simulation. This was because of higher mortality rate of trees in 3-PG compared with DT simulations. In 3-PG the final number of stems at the age 63 was 724 stems per ha but in DT simulation the final number was796 stems per ha. The autumn decline of photosynthetic capacity is considered in Process Based Models (PBM) like 3-PG. Autumn decline of photosynthetic capacity is caused due to severe frosts (Bergh *et al*., 1998). In the 3-PG model, the autumn decline is calculated using negative effect of freezing temperatures. The negative effect of freezing temperatures is calculated by number of frost days (Landsberg, 1986; McMurtie *et al*., 1994; Coops *et al*., 1998). Due to autumn decline the photosynthetic capacity declines by about 15% of the normal capacity for *Norway spruce* (Bergh *et al*., 1998). However the modifications for physiological process like autumn decline in empirical models like DT is more close to reality. So the loss of growth can take any values in between 0 and 1. Since the frost modifier in 3-PG model can take only extreme values, will lead to underestimation of NPP. However, the root DM was slightly overestimated in 3-PG. This can be explained by low parameter value of root turnover rate (11, 5% per year) used in 3-PG. The R^2 values obtained for foliage DM, stem DM, root DM and total DM are 0, 82; 0, 94; 0, 7 and 0,73 respectively (fig 8-11). The highest efficiency is obtained in prediction of stem DM (R^2= 0, 94) and least efficiency in predicting root DM (R^2= 0, 7).

Table 3. Comparison of simulated Dry Mass (tonnes DM/ha) using the DT model with reference run (tonnes DM/ha) using 3-PG model. In the 3-PG simulation, climatic variables were from the time period 1961-1990

Age	**Foliage DM**		**Stem DM**		**Root DM**		**Total DM**	
	DT	3-PG	DT	3-PG	DT	3-PG	DT	3-PG
34	19.0	19.0	136.2	136.2	38.4	38.37	193.6	193.6
39	16.1	16.9	132.3	138.7	36.6	47.00	184.9	203.4
44	19.1	18.9	172.0	164.4	47.0	53.51	238.1	237.7
48	21.4	19.7	210.2	184.1	56.0	56.40	287.9	260.3
49	14.9	16.6	147.0	157.6	39.5	52.23	201.5	261.8
54	16.8	17.3	179.7	180.1	47.3	55.80	243.8	254.0
59	18.7	19.4	214.4	205.5	55.5	59.84	288.7	285.6
63	19.4	20.4	238.4	224.4	60.5	60.78	318.4	305.6

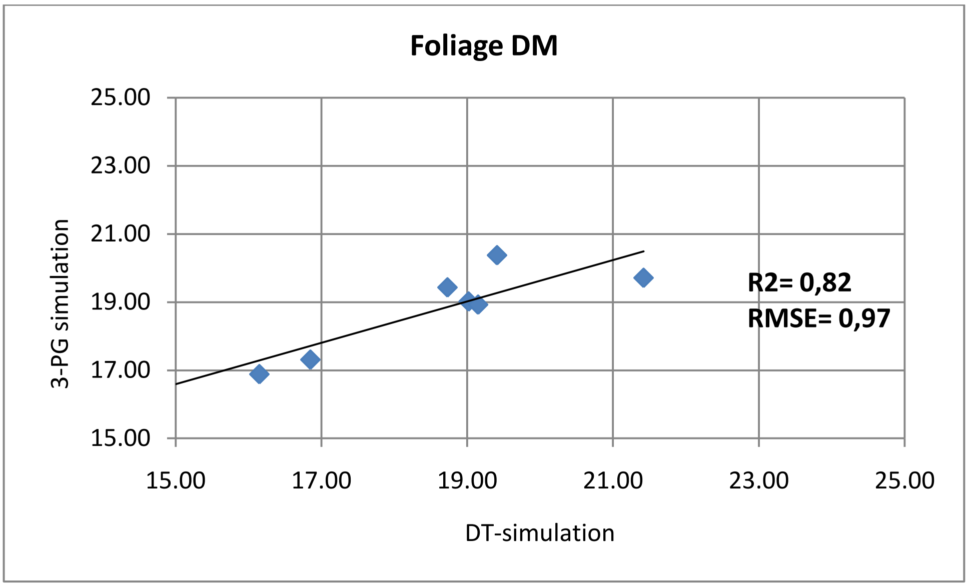

Figure 9, Efficiency of prediction of Foliage DM

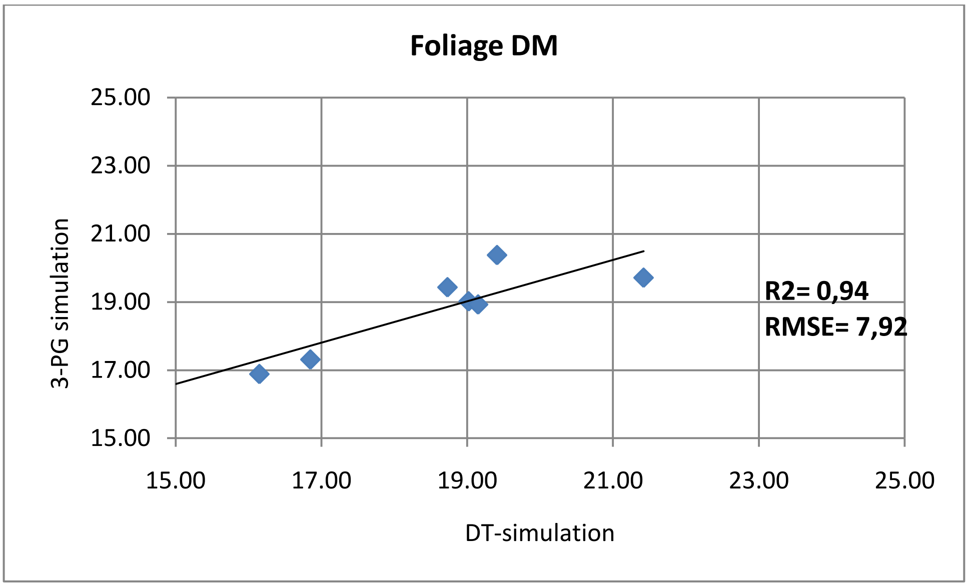

Figure 10. Efficiency of prediction of Stem DM

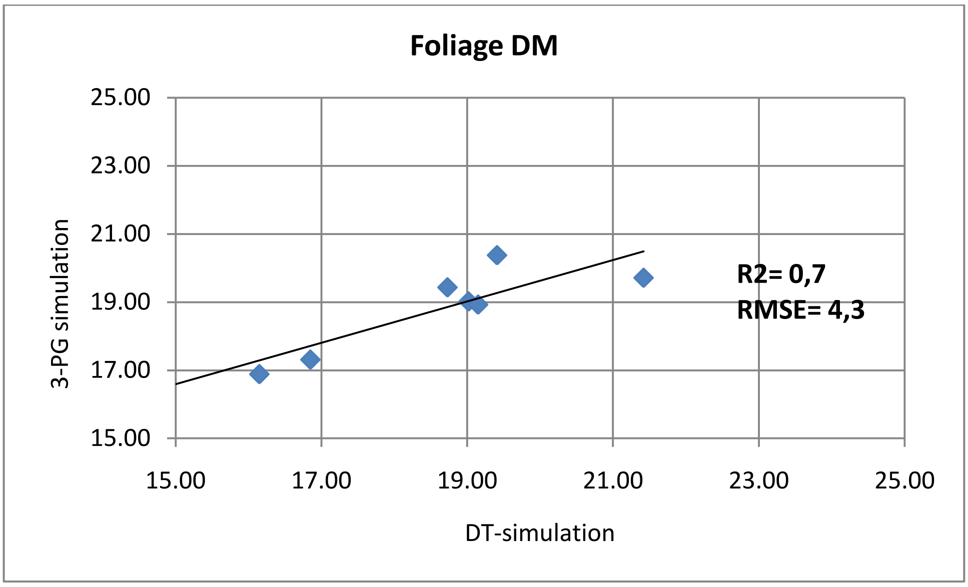

Figure 11, Efficiency of prediction of Root DM

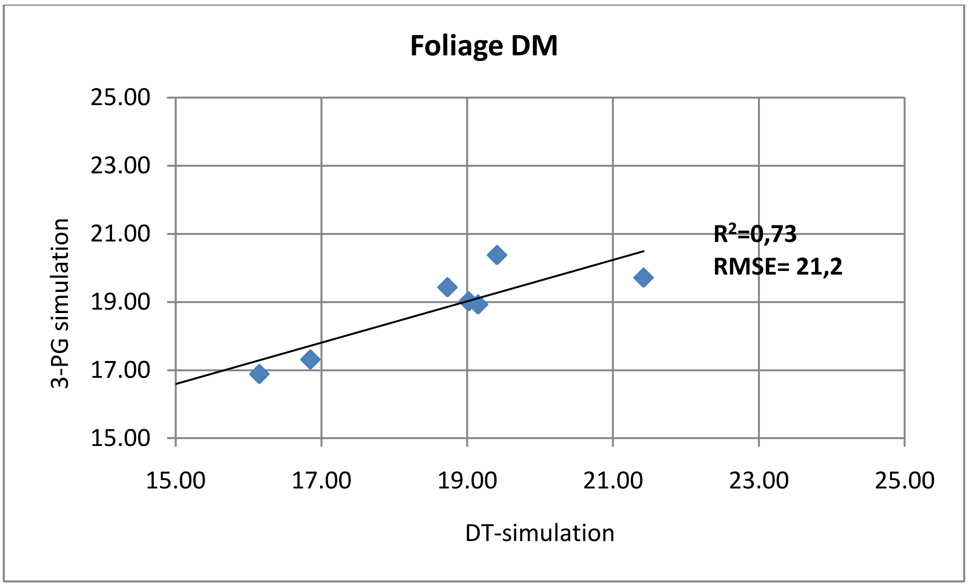

Figure 12. Efficiency of prediction of Total DM

4.2 Predicted NPP in reference run compared with scenario runs

A2- and B2-scenarios scenarios showed higher value of NPP than for the reference period (Figure, 12) and the A2-scenario showed higher NPP values than the B2-scenario.NPP in reference the scenario ranged between 0.69 to 0.83 kg C/m^2/year. The lowest value of NPP was during the fourth 5-year period for both for the reference and B2-scenario but during this period A2 had high NPP. The highest NPP in all scenarios is during first growing period (Table 3).

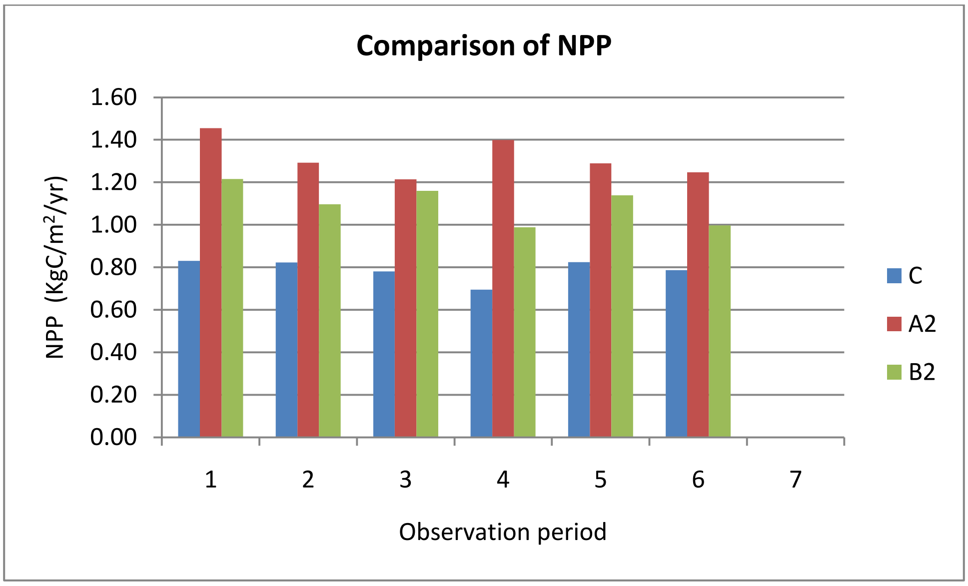

Figure 13. Comparison of NPP (kg C/m^2/yr) simulated using 3-PG model for reference run (C scenario) with A2- and B2-scenarios. The observation period is the 30 years of observation in five year averages values (see table 3).

Table 4. Comparison of NPP in kg C/m^2/yr, percentage change in NPP in A2- and B2-scenarios when compared with the reference scenario.

			NPP			% change in NPP	
Year	***Stand age***	***Ref***	***Year***	***A2***	***B2***	***A2***	***B2***
1961-65	34-38	0.83	2071-75	1.5	1.2	75.3	46.5
1966-70	39-43	0.82	2076-80	1.3	1.1	57.0	33.3
1971-75	44-48	0.78	2081-85	1.2	1.2	55.5	48.4
1976-80	49-53	0.69	2086-90	1.4	1.0	101.6	42.4
1981-85	54-58	0.82	2091-95	1.3	1.1	56.5	38.3
1986-1990	59-63	0.79	2096-00	1.2	1.00	58.7	26.8

The highest increase in NPP in relations to simulations with reference climate is during 2086-2090 period (102%) in A2-scenario. This is because of lower summer temperature particularity during this period for A2-scenario. This will result in increased growing period for trees. During this period the summer rainfall is higher in A2-scenario especially in June. The highest increase in NPP for the B2-scenario is during 2081-2085 period (48%). This is caused by lower summer temperature and higher winter temperature during this period in the B2-scenario. The rainfall during this period is almost same for both scenarios. These conditions favor growth of trees which result in higher NPP for B2. The B2-scenario shows uniform range of increase in NPP during the whole observation period. The range of relative increase in NPP is between 27 to 48%. But in the A2-scenario the increase in NPP is not uniform for all the observation period. The percentage increase in NPP ranges between 55 to 102%.

4.3 Sensitivity Analysis

4.3.1 Rainfall Sensitivity analysis

A2-scenario showed a reduction in NPP when the model was run with reference rainfall for the whole growing period (Table 4). However, A2 showed a slight increase in NPP (0.38%) with reference rainfall during the first 5-year period. This may be due to the initial soil moisture conditions, which was outside the observation range used in the sensitivity analysis. In the B2 scenario, there was an increase in NPP during the first three 5-year periods and the sixth observation period. But during fourth and fifth 5-year, NPP was reduced. A2-scenario predicts higher rainfall; this will reduce the water stress for trees and hence positively influence NPP (Esprey *et al*., 2004). So for A2-scenariothe NPP is influenced by water availability to some extent. Analyzing rainfall sensitivity with elevated temperature (3.2^{o}C higher than reference temperature in average), will also increase the soil evaporation and water stress resulting reduced growth of trees. Water stress also increases the partitioning to roots (Esprey *et al*., 2004).

Table 5. Rainfall sensitivity analysis, Values shown are NPP (Kg C/m^2/yr) for reference and scenario runs and the relative change in NPP (%) when the 3-PG model was run with reference rainfall for A2- and B2-scenarios. All other variables except total monthly rainfall are changed according to scenario prediction.

Year	**NPP A2**			**NPP B2**		
	Reference Rainfall	***Scenario rainfall***	***% change***	***Reference Rainfall***	***Scenario rainfall***	***% change***
2071-75	1.5	1.4	0.4	1.3	1.2	3.5
2076-80	0.9	1.3	-28.8	1.1	1.1	3.2
2081-85	0.5	1.2	-56.5	1.2	1.2	1.1
2086-90	1.1	1.4	-20.5	0.8	1.0	-16.4
2091-95	1.1	1.3	-12.6	0.9	1.1	-20.2
2096-00	1.0	1.2	-23.3	1.3	1.0	28.3

In B2-scenario the average increase in temperature is around 2.3 ^{o}C, which is less than A2-scenario. The rainfall in B2-scenario is also less than that in A2-scenario (see figure 6) and more similar to reference climate. This is the main explanation for the minor increase in NPP for B2-scenario. The increase in total monthly rainfall will result in an increase in available water for the trees (Bergh *et al*., 2010).

4.3.2 Temperature sensitivity analysis

The 3-PG model uses daily maximum and minimum temperatures to take diurnal temperature variation in to account while calculating NPP. According to Churkina and Running (1998), temperature is a major measure of climate to be used in growth models. Calculation of NPP is a complex function of several processes, where temperature affects many of these processes (Ladanai and Argen, 2003).

There was an increase in NPP for the A2-scenario, when the model was run with reference temperature (Table 5). Except for the fourth 5-year period, all periods showed positive change in potential NPP. In B2-scenario the relative change in NPP was small; expect for second and sixth 5-year periods (10.6% and 6.02% respectively).Increased temperature in A2- and B2-scenario will lead to an extension of the growing season in spring and autumn. Bergh *et al*., (2010) calculated this extension of growing season to be approximately two months in total. The extended growing season will result in increased interception of incoming solar radiation, which will increase photosynthesis and increase NPP and production of forest trees.

Table 6. Temperature sensitivity analysis, Values shown are NPP (Kg C/m^2/yr) for reference and scenario runs and the relative change in NPP (%) when the 3-PG model is run with reference temperature for A2- and B2-scenarios. All other variables except monthly average temperature are changed according to scenario prediction.

Year	**NPP A2**			**NPP B2**		
	Reference Temp	***Scenario Temp***	***% change***	***Reference Temp***	***Scenario Temp***	***% change***
2071-75	1.5	1.4	0.01	1.2	1.2	-0.9
2076-80	1.3	1.3	4.5	1.2	1.1	10.6
2081-85	1.4	1.2	11.7	1.1	1.2	-2.4
2086-90	1.3	1.4	-8.7	1.0	1.0	-3.0
2091-95	1.4	1.3	10.9	1.1	1.1	-0.9
2096-00	1.4	1.2	14.1	1.0	1.0	6.0

4.3.3 Soil fertility Sensitivity Analysis

Increase in soil fertility increases the biomass allocation to stem and decreases allocation to roots (Esprey *et al*., 2004). 3-PG outputs were highly sensitive to soil fertility (Espery and Smith, 2002; Esprey *et al*., 2004). In table 6 reference fertility is, the NPP of the trees when the 3-PG model is run with soil fertility value (0.5) for A2- and B2-scenarios. In scenario fertility the 3-PG model was run with soil fertility predicted by scenarios (0.6). In both scenarios the relative change in NPP was reduced when the model was run with reference soil fertility (Table 6). For both scenario runs, the fertility level was kept at a constant level of 0.6. Therefore, the decrease in NPP was in the same range for both scenarios.

Table 7. Soil fertility sensitivity analysis, Values shown are NPP (Kg C/m^2/yr) for reference and scenario runs and the relative change in NPP (%) when the 3-PG model is run with reference soil fertility (0.5) for A2- and B2-scenarios. All other variables except soil fertility are changed according to scenario prediction.

Year	**NPP A2**			**NPP B2**		
	Reference Fertility	***Scenario Fertility***	***% change***	***Reference Fertility***	***Scenario Fertility***	***% change***
2071-75	1.3	1.5	-7.0	1.1	1.2	-7.1
2076-80	1.2	1.3	-6.8	1.0	1.1	-7.1
2081-85	1.1	1.2	-6.6	1.1	1.2	-6.9
2086-90	1.3	1.4	-6.7	0.9	1.0	-7.0
2091-95	1.2	1.3	-6.6	1.0	1.1	-6.9
2096-00	1.2	1.2	-6.6	0.9	1.0	-7.0

4.4 Comparison of LAI

According to Spinnler *et al*., (2002) LAI is a major determinant variable which highly influence on various ecosystem level processes. Any effect in climatic and site related factors will affect LAI. Esprey *et al*., (2004) found that in the 3-PG model, LAI is moderately sensitive to fertility rate of soil. For both scenarios the LAI increased during the simulation period (Table 8). But at the fertility level 0.7 the LAI tends to reduce during the 5^{th} and 6^{th} growing periods. This indicates that if fertility level increases more than a certain level, the trees cannot utilize the advantage of it because increased fertility level also leads to increase in need of other resources such as water, solar radiation etc. But in this study the other factors are kept constant. McMillan *et al*., (2008) have indicated that if an increase of one limiting resource is not accompanied by simultaneous increase in other limiting resources, these other resources will limit the production instead.

Table 8. Comparison of LAI, Simulated LAI of trees when initial soil fertility level is changed. The 3-PG model is run with three fertility level for A2- and B2-scenarios. 0.5- Reference soil fertility, 0.6- Scenario soil fertility and 0.7- Increased soil fertility.

Year	**A2 LAI**			**B2 LAI**		
	Fertility 0,5	***Fertility 0,6***	***Fertility 0,7***	***Fertility 0,5***	***Fertility 0,6***	***Fertility 0,7***
2071-75	6.3	6.7	7.1	6.0	6.4	6.7
2076-80	8.4	9.6	10.6	7.5	8.5	9.4
2081-85	9.8	11.2	12.6	8.4	9.7	10.9
2086-90	9.3	10.6	12.0	8.1	9.4	10.5
2091-95	10.3	11.8	13.3	8.4	9.7	11.0
2096-00	10.0	11.5	13.0	8.3	9.6	10.8

4.5 Comparison of predictions of potential NPP between 3-PG and BIOMASS models

The 3-PG simulations showed higher variation than the BIOMAS simulation for both scenarios (Table 8). The mean values were also higher for 3-PG than for BOMASS for both scenarios. The relative change in potential NPP in scenario runs, in relation to reference run, was around 15% (ECHAM-B2)-17% (Had-B2) and 28% (Had-A2)-34% (ECHAM-A2). Had is the simulation done with regional climate scenario based on HadAM3H General Circulation Model (GCM) and ECHAM is the simulation done with regional climate scenario based on ECHAM/OPYC3 GCM (Blennow *et al*., 2010).

Table 9. Comparison of relative change in NPP between the two models, 3-PG and BIOMASS.

Scenario	**3-PG**		**BIOMASS**	
	Range	***Mean***	***Range***	***Mean***
A2	55.5-101.6	67.4	13.3-41.8	24.4
B2	26.8-48.4	39.3	10.7-29.7	18.6

Source for BIOMASS data: Bergh *et al*., (2010)

According to Bergh *et al* (1999), the BIOMASS model is adjusted to photosynthetic decline in autumn and recovery of a winter damaged photosynthetic apparatus in early spring. In 3-PG model, the autumn decline is calculated using negative effect of sub freezing temperature. The negative effect of sub freezing temperature is calculated by number of frost days. The value of frost days is either 0 (system shutdown) and 1 (no constraints) (Landsberg, 1986; McMurtie *et al*., 1994; Coops *et al*., 1998). There are no in between values for negative effect of temperature. The temperature dependent recovery of photosynthetic capacity in spring in not considered in the same way in 3-PG either. This will lead to biased estimates of NPP in the 3-PG model. Parameters in the 3-PG model were adjusted so dry mass production follow simulated values of the DT-model. Output values from DT of foliage dry mass and LAI could have been overestimated and mortality rate might be underestimated. Since these values of LAI was used in 3-PG, this might be another reason for higher estimations of potential NPP in the 3-PG model compared to BIOMASS.

BIOMASS has no feed-back mechanism to soil nutrient dynamics, which means that photosynthesis is not restricted by nutrient limitations (McMurtrie, 1985). In the same time elevated temperature will increase soil temperature and biological activity and therefore mineralization and increased nutrient availability (Freeman *et al*., 2005). For the simulations in 3-PG the soil fertility was held at a constant level for whole simulation period, 0.5 for reference run and 0.6 for simulation runs. However, the soil fertility will probably increase during the observation period due to increased nutrient cycling. Since the soil fertility is kept constant at a medium value through the whole observation period, the model predicts higher initial growth.

BIOMASS model is more sensitive to canopy related characteristics, where BIOMASS considers tree foliage in three separate layers with different levels of incident photon flux density from sunlight (see eqn 6-8). But in 3-PG model the canopy layer is considered as a single layer. This can be a reason for higher relative increase of NPP in 3-PG model. The basic equations in BIOMASS model are canopy photosynthesis equations but that in 3-PG model is carbon balance equation. The carbon balance equations were more sensitive to change in climatic (CO_2-response) and soil fertility factors than the canopy photosynthesis equations. The carbon balance equations used in 3-PG model (eqn 3-5) were based on dry mass produced (carbon sequestration), root turnover, allocation of NPP to various parts of trees, litter fall rate etc. The canopy photosynthesis equation used in BIOMASS model (eqn 7-9) were based on duration of sunshine, daily respiration of trees, and incident photon flux density on tree canopy. Under elevated levels CO_2 and soil fertility the carbon sequestration and allocation will be more sensitive than daily respiration, incident photon flux density on tree canopy.

5. Conclusion

This study demonstrates how the predictions of Process Based Models (PBMS) vary according to their mechanism of calculation. This study has potential to expand towards other similar PBMs in forestry and towards other tree species. The most important part of the study is the comparison between the two PBMs 3-PG and BIOMASS. The change in the important calculation mechanism such as photosynthetic decline and soil nutrient dynamics has resulted in high variation in prediction of NPP between these two models. Both the models predict the increase in NPP in the future. According to 3-PG the mean percentage increase in NPP is around 67 % (A2-) and 39% (B2-). In reality we can expect the increase in NPP between these two values in future. This will result in increased harvests and income in future in southern Sweden.

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Appendix 1, Values of important parameters in 3-PG for *Picea abies*

Description of parameter	**3PGPJS name**	**Units**	**Valuefor *Picea abies***	**Reference**
Biomass partitioning and Turnover				
Allometric relationships and partitioning				
Ratio of foliage stem partitioning D= 2cm	pFS2	-	0,8	
Ratio of foliage stem partitioning at D=20cm	pFS20	-	0,7	
Constant in the stem mass vs diameter relationship	aS	-	0,025	
Power in the stem mass vs diameter relationship	nS		2,82	
Maximum partitioning of NPP to roots	PRx	-	0,9	
Minimum fraction of NPP to roots	PRn	-	0,26	Livonen *et al.*, 2008
Litterfall and root turn over				
Maximum litterfall rate	gammaFx	1/month	0,014	
Litterfall rate at t=0	gammaF0	1/month	0,001	
Age at which the litterfall has median value	tgammaF	Months	24	
Average monthly root turnover rate	gammaR	1/month	0,0096	
NPP and conductance modifiers				
Temperature modifier				
Minimum temperature for growth	Tmin	deg. Celsius	-3	Bergh *etal.*, 2003
Optimum temperature for growth	Topt	deg. Celsius	20	
Maximum temperature for growth	Tmax	deg. Celsius	43	Bergh *etal.*, 2003
Frost modifier				
Days of production lost per frost day	kF	Days	1	
Age Modifier				

Maximum stand age used in age modifier	MaxAge	Years	120	
Power of relative age in function of fAge	nAge	-	3,675	
Relative age to give fAge=0,5	rAge	-	0,95	
Stem mortality and self thinning				
Mortality rate for large t	gammaNx	%/year	1,5	
Seedling mortality rate (t=0)	gammaN0	%/year	0	
Age at which mortality rate has median value	tgammaN	Years	20	
Max stem mass per tree åt 1000 trees/ha	wSx1000	Kg/tree	350	
Power in self thinning rule	Thinpower	-	1,5	
Canopy structure and processes				
Specific leaf area				
Specific leaf area at age=0	SLA0	M2/kg	5	Bergh *et al.*, 2003
Specific leaf area for mature leaves	SLA1	M2/kg	3,5	Bergh *et al.*, 2003
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	M2/kg	3	
Light interception				
Age at which canopy cover	fullcanAge	Years	10	.Eliasson *et al.*, 2005
Wood and stand properties				
Branch and Bark fraction				
Branch and bark fraction at age 0	fracBB0	-	0,25	
Branch and bark fraction for mature stand	fracBB1	-	0,15	
Age at which (fracBB=fracBB0+fracBB1)/2	tBB	Years	3	
Basic density				
Minimum basic density for young trees	rhoMin	t/m3	0,400	
Maximum basic density for older trees	rhoMax	t/m3	0,400	
Age at which rho= (rhomin+rhomax)/2	Trho	Years	60	

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